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Dendrometer as a water stress indicator for apple trees

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ABSTRACT

The use of dendrometers to measure the stem diameter (SD) of trees provides information about their actual water stress levels. The Scholander chamber is currently the gold standard for measuring stem water potential and thus for quantifying the water status of trees, despite being a laborious method, especially for apple trees. The aim of this study was to analyze dendrometer data to assess the water stress in drip-irrigated 'Gala' apple trees (Malus x domestica Borkh). A trial was performed in Grens, Switzerland, during the 2022 season. Three different irrigation treatments were applied (T1 = 100 % soil moisture-based irrigation, T2 = 30 % less than T1, and T3 = without irrigation). The irrigation treatments notably affected fruit production. Trees in T3 exhibited a significant yield loss of 26 %, whereas treatment T2 yielded 13 % less than the reference treatment T1. Although daily changes in the SD correlated with vapor pressure deficit (VPD) (r^2 = 0.84), limiting the amount of water available to the plant disrupted this correlation (r^2 = 0.27), with stem water potentials dropping by −1.7 MPa and a noticeable shift in stem movement (shrinking/expanding). Finally, we developed a suitable linear regression model that compared the shift in slope and offset of regression lines fitted for SD and VPD during initial non-stressed conditions (reference) with those under stressed conditions in order to estimate stem water potential. By integrating dendrometer parameters with VPD, the model effectively predicted stem water potential values. These findings suggest that dendrometers are effective indicators of water stress in apple trees. Further refinement of the model in field conditions could enhance the use of these sensors for irrigation management, providing more precise guidance on the timing and amount of water applied.

1. Introduction

Climate change currently poses a significant challenge to the agricultural sector, particularly for irrigated crops. Irrigation represents through far the largest water consumption in agriculture, accounting for roughly 70 % of global water withdrawals (Simionesei et al., 2020). Nevertheless, the volume of water allocated to irrigation often leads to substantial losses due to the inadequate management of irrigation systems. Precision irrigation or smart irrigation holds the potential to provide a more sustainable method of water utilization. These systems integrate sensors that indicate water status directly by plant-based sensors or indirectly by soil moisture sensors (Parkash and Singh, 2020), which are used to efficiently steer irrigation systems in real time (Mason et al., 2019).

Soil moisture sensors measure either soil water matric potential or volumetric soil water content and are typically used to display soil moisture levels, providing guidance on how much water is needed for daily irrigation (Dursun and Ozden, 2011). The volume of applied water must be sufficient to ensure that the yield and fruit quality are not compromised by insufficiency or excess of water (Thompson et al., 2007). Pre-established thresholds, based on knowledge of each crop and soil type, help prevent both under- and over-irrigation based on soil moisture data. The effectiveness of such irrigation systems has been confirmed for several crops (Allen and Pereira, 2009; Centeno et al., 2010; Dietrich et al., 2018; Mausbach et al., 2022; Reid and Kalcsits, 2020), including apple (Domínguez-Niño et al., 2020; Jiang and He, 2021; Majone et al., 2013). However, such methods only indirectly monitor the plant's requirements. The efficiency of irrigation systems may be further improved by using plant-based systems or combining them with soil moisture sensors, as plant water stress is often not directly

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correlated with soil moisture content. In particular, perennial crops can access water at a greater depth than sensors, which are usually installed at a depth of 50 cm (Cepuder and Nolz, 2007).

The best way to assess a plant's responses to water availability has been proposed to be through physiological indicators (plant-based sensors) (Doltra et al., 2007; Jones, 2004; Ortuño et al., 2010). The availability of water in plant tissues can be assessed by measuring stem water potential (Ψ_{stem}), and this is recognized as the most reliable method for obtaining the water status of the plant (Améglio et al., 1999; Moriana et al., 2012; Pôças et al., 2020). Reliability, as well as the relatively low cost of the device, is responsible for its popularity (Conejero et al., 2011; Naor and Cohen, 2003; Noar et al., 2003). Measurements are mainly performed using a Scholander chamber, which measures the "*sap extruded from the xylem by gas pressure in the leaves*" and reflects the tension at which the xylem transports water (Scholander et al., 1965). This transport operates within a hydraulic continuum between the soil and the atmosphere, depending on water loss due to transpiration and water uptake by the roots (Jancoski et al., 2022). Despite the wide use of the Scholander chamber, using it is extremely laborious. Reliable data can only be obtained with this method if the required steps for data collection are carried out precisely and at a high speed to ensure adequate analysis of the entire sample (Turner, 1988). Another aspect that can cause interference is the timing of the data collection. Predawn and midday are the ideal times to determine the water status of the leaves (Jancoski et al., 2022). Most importantly, these measurements cannot be used to automate irrigation because they depend on human operations, at least with this device.

Daily variations in the diameter of tree stems measured by means of dendrometers can also provide information about the plant's water status. The plant's transpiration process starts at sunrise, and the stem diameter (SD) decreases throughout the day; thus, the dendrometer can describe the plant's daily amplitude, that is, daily shrinkage. After sunset, SD increases due to the recovery of lost water, which is referred to as swelling of the stem. According to Kramer (2012), data obtained with dendrometers can describe tree stems' total shrinkage—swelling and deposition of the xylem, phloem, and periderm. Several studies have used parameters such as maximum daily shrinkage (MDS) or daily growth (Corell et al., 2019; Doltra et al., 2007; Fereres and Goldhamer, 2003; Fernández and Cuevas, 2010; Goldhamer and Fereres, 2001; Ortuño et al., 2010). However, none of these approaches express water stress or stem water potential. The correlation of derived parameters of dendrometer sensors with climatic parameters, is generally quite high, while the correlations with water potential are not very reliable. Further, the parameters derived from the dendrometer are not ideal for all stages of crop development.

Usually, MDS shows a pattern in which the values tend to increase with rising water stress. However, this pattern was not observed by Moriana and Fereres (2002). They found no significant differences in MDS between stressed and non-stressed young olive trees, whereas Moriana et al. (2010) observed that the MDS of water-stressed trees initially increased before decreasing below the values found in the control trees in mature olive trees. This was also described in young peach trees, in which the MDS values resulted in a reversed pattern (Goldhamer and Fereres, 2001). In other words, as the soil dries and water stress of the plant increases due to prolonged dry climatic conditions, MDS values tend to decrease. However, the shrinkage phase of the daily stem diameter usually increases with increasing climatic water stress. A study carried out during the fruit development phase of apples also observed this reversed pattern of MDS (Wheeler et al., 2023). It is likely that the combination of higher soil matric potential, which limits the availability of water to replenish the stem at night, and the depletion of water stored in stem tissues limits the recovery of the reduced diameter caused by high transpiration rates during the day, thereby reducing the expansion phase. This pattern was calculated by computing the difference between the maximum SD values of the control and stressed trees (De Swaef et al., 2009). This modified MDS reflects the stress applied in the experiment more accurately. However, this calculation always requires a control plot, which makes it less applicable in practice.

Ortuño et al. (2010) explored this theory further and developed a method that uses the concept of signal intensity. The absolute MDS is normalized by taking the non-limiting soil water conditions treatment as a reference (control) and dividing the MDS values from stressed trees by the reference values. A problem related to this methodology, according to the authors, is that MDS is affected by weather conditions. For example, they highlighted that MDS absolute values might remain consistent for trees in well-watered treatments facing high evaporative demands and at levels similar to those in stress conditions on days with low evaporative demands.

The tree growth rate (TGR) has also been used in studies that aim to report the water status of trees. According to some authors, TGR is more sensitive to stress than the other parameters and is recommended for stress evaluation in young trees (Fereres et al., 1999; Fernández and Cuevas, 2010; Moriana and Fereres, 2002). However, the TGR varies greatly between days, making it difficult to interpret and utilize the data. Recognizing this disadvantage, Corell et al. (2019) implemented the frequency of different TGR ranges instead of using raw data. This approach reduces TGR data variability and is independent of the evaporative demand and phenological stage of the plant. Although this approach is very effective in reporting stress, further research is required to confirm its usage as a water stress indicator in a smart irrigation system.

Tree water deficit (TWD), also known as tree water deficit-induced reversible stem shrinkage (Zweifel, 2016), is considered a better water stress indicator for trees than MDS and has been widely used to report water stress in forestry experiments, showing close correlations with Ψ_{stem} (Zweifel, 2016). However, the reliability of this parameter for fruit trees remains uncertain. Nehemy et al. (2021) reported that TWD can vary depending on the phenological stage of the tree and is further affected by soil moisture.

Despite the credibility of the parameters derived from the dendrometer, how well these parameters are suited to steer irrigation remains uncertain. This needs to be considered with regard to future automation of irrigation systems. Although some parameters derived from dendrometers recognize water stress more quickly than other physiological variables, stablishing a threshold based on these values continues to be a challenge, as noted by Noar et al. (2003). Nevertheless, there has been some success in the use dendrometer-derived parameters to indicate water stress in crops, such as grapes, in particular with metrics such as TWD (Ohana-Levi et al., 2022).

The aim of the present research was to investigate the use of dendrometer-derived parameters as water stress indicators based on field conditions. Our main aim was to evaluate the relation between stem diameter variation and vapor pressure deficit (VPD) having the Ψ_{stem} as standard baseline for water status of trees. We aimed to improve the understanding of the interactions between these parameters to facilitate their implementation in future irrigation automation systems.

2. Materials and methods

2.1. Site

The experiment took place on a farm close to the Lake of Geneva region, Switzerland (46° 23' 48.84" N, 6° 11' 45.57" E). The data were collected between July and August 2022. The region is approximately 400 m above sea level and is characterized by an average temperature of 11.2°C, with an average rainfall of about 1030 mm. It is classified as a temperate oceanic climate (Cfb) according to Köppen-Geiger (Kottek et al., 2006).

2.2. Experimental setup

The research involved 45 (3 ×15) Gala variety apple trees (Malus x domestica) planted in 2011(Fig. 1). To prevent the confounding influence of edge effects, each plot was separated by a distance of at least two trees. Tree density was 2083 trees/ha with individual tree spacing at 1.2 m and row spacing at 4 m. The soil composition in the plots comprised 48 % silt, 41 % sand, and 11 % clay, maintaining a pH of around 7.7 (data provided by the farm). A weather station was positioned in the center of the experimental area (46° 23' 49.01" N, 6° 11' 45.38" E). The data set includes measurements of air temperature and humidity (Sensirion SHT75, Sensirion, Stäfa, CH), wind speed and direction (Davis 6410 Anemometer, Davis, Hayard, USA), and solar radiation (Apogee SP212, Apogee, Logan, USA).

2.3. Treatments

The study utilized three randomized blocks (A, B, and C), representing one replicate with three irrigation treatments each (T1, T2, and T3), forming a Latin square design. One dripper line with a spacing of 0.75 m between the drippers irrigated the trees. Three irrigation treatments were implemented and monitored with soil moisture using three soil moisture sensors per treatment (Watermark, Irrometer Company, Riverside, EUA) were installed at a distance of 15 cm from the closer dripper in front of the tree. These sensors were connected to and evaluated by an automatic system (Sensorscope, Lausanne, https://www.climaps.ch/). The first treatment (T1 = 100 % irrigation) served as the control, where the system was set to maintain soil moisture between – 20 to −40 KPa. In the second treatment (T2 = T1 - 30 %), we irrigated only 70 % of the water applied in T1, achieved by adjusting the irrigation line. The third treatment (T3 = without irrigation) was the most drastic, allowing watering only when stress levels were critical (below −2.5 MPa). For this, we used water passage through blind tubes, swapping when irrigation was required via a manual open/close valve.

2.4. Tree productivity

2.4.1. Leaf area

The leaf area of two trees per plot was calculated using manual measurements of each branch with the assistance of a digital caliper (Kraftwerk, Mönchaltorf, Switzerland). Subsequently, these data were implemented in an equation generated from a linear regression, based on data collected in the same area from previous years, by leaf area surface sensors (LAI-2250 Optical Sensor Plant Canopy Analyzer, Bad Homburg, Germany) to obtain leaf area/cm^2 (Sfol) (Eq. 1). The average leaf area of all trees was divided by the area in m^2/tree resulting in an estimated LAI of each treatment.

$$Sfol = 0.253x^{0.755} \quad (1)$$

Sfol= leaf area per cm^2

x = branch/stem diameter

2.4.2. Fruit diameter

The diameter of the fruit was measured by selecting two trees from each plot (n = 3), resulting in a total average of 18 trees. Each tree had a branch selected with at least four fruits. The diameter per fruit was measured once per week with a digital caliper (Kraftwerk, Mönchaltorf, Switzerland). Overall, the diameter of the fruits was collected over a period of 9 weeks. Only the last measurement was considered for the presented evaluation.

2.4.3. Yield

The harvest took place at the end of August 2022 on the farm. The experimental plots were harvested on 24 August 2022. This was carried out in collaboration with the farm. The number of fruits was counted and fruits were weighed separately for each tree in the experiment (n = 45).

2.5. Water stress indicators

2.5.1. Stem water potential

Ψ_{stem} measurements were taken weekly around noon, following the methodology described by (Moriana et al., 2012). All trees were measured on the same day (start: 11:00 am; end around: 2:15 pm). For each tree in the experiment (n = 45), we selected a healthy leaf, in the shade part of the tree, during the entire collection period. This leaf was covered using an aluminum-coated plastic bag for a minimum of 30 min. After the holding period, the leaf was removed along with its petiole. The petiole was later cut off using a sharp blade. Subsequently, this leaf, still wrapped, was placed in a Scholander chamber (Scholander chamber model M-600, 1725, Geary Stress, Albany, USA), which was increasingly pressurized with compressed air until liquid was observed at the

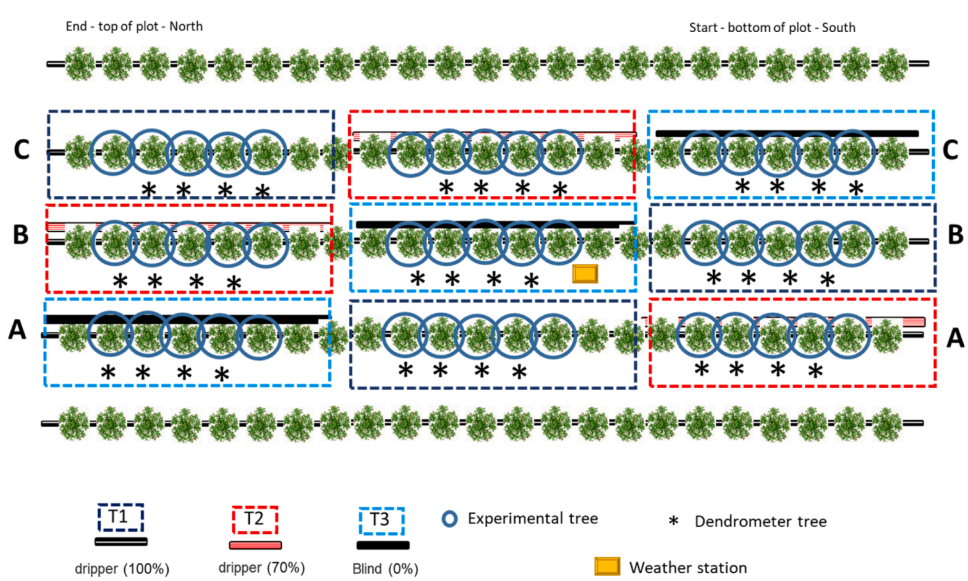

Fig. 1. Experiment scheme with three blocks A, B and C in Grens, Switzerland.

protruding end of the petiole. The requisite pressure, indicated on the gauge by the bar reading, was recorded for each leaf, thereby symbolically representing the tree itself, and then converted to MPa.

2.5.2. Dendrometer-derived parameters

2.5.2.1. Equipment description. Of the 45 trees initially sampled, only 36 were equipped with dendrometers. The SD of 36 trees was measured every 15 min by means of dendrometer sensors. These sensors were constructed by Agroscope with the use of a linear potentiometer (Model SLPT 25 mm, Opkon, Istanbul, Turkey), which was fixed on an aluminum frame, allowing movement in one horizontal plane of the potentiometer (Fig. 2). In each of the three blocks (A, B, and C), 12 central trees were selected and mounted with dendrometers, four per single plot. The total number of trees equipped per treatment in the experiment was thus 12. The sensor demonstrated a resolution of + /- 6.1 µm. Each single plot had four sensors fixed on the stem of the apple trees. A rubber band (2.5 mm) was tied up to secure the fixation. Stem radius was measured as a voltage signal and stored by an Agribase data logger version 2.327 (Agriscope, Mauguio, France). Data were transmitted via a middle-wave radio frequency (916 MHz). A modem transferred the data to an online platform (www.agriscope.fr), where they were linearly converted to a numerical scale (diameter [µm]). Fig. 3 illustrates the relative SD curves obtained by the sensor for T1 (tree label = T1A1), T2 (tree label = T2A2), and T3 (tree label = T3A3) treatments during the trial.

2.5.2.2. Data processing. The dendrometer-recorded phases of stem shrinkage and expansion underwent preprocessing to address signal quality and sensor positioning. R version 4.0.1/2 (R Development Core Team 2018) software and dendRoAnalyst (Aryal et al., 2020) package were employed to identify jumps in the continuous values forming the daily curve. Of the 36 sensors installed on the trees, only 28 were used after the data quality analysis. After removing all jumps in the data ("jump.locator" function), the data normalization was performed, setting the smallest value to 0 and classifying it based on time of day (night = 21:45–05:30, sunrise = 05:31–07:00, day = 07:01–20:00, sunset = 20:00–21:45) in local summer time. This classification enhanced the daily observation of the stem shrinkage and expansion phases. Using the dplyr package (Wickham et al., 2023) data normalization ensured a consistent starting point (= 300 µm) for all 28 trees with processed dendrometer data, mitigating negative values resulting from daytime decreases. Focusing on the sunrise and sunset periods, the maximum value per day from each tree was analyzed. The average, minimum, and maximum of the TWD was calculated with the proc_dendro_L2 function from the treenetproc R package (Zweifel et al., 2016, Knüsel et al., 2021). The maximum SD, minimum SD, and MDS (MDS = max value $_{(n)}$ – min value $_{(n)}$) were obtained based on basic statistical parameters (mean, max, and min).

Fig. 2. Dendrometer sensor mounted on the apple tree in Grens, Switzerland.

To observe the tree's response in situations where water stress was high, the dendrometer data were separated and analyzed over two periods. Based on the Ψ_{stem} data, the experiment was separated into two periods: one period was named the unstressed period, during which the water stress shown by the Ψ_{stem} data was above −1.5 MPa; the second was named the stressed period, during which the water stress shown by the Ψ_{stem} data was below −1.5 MPa.

2.6. Statistical analysis

The variability of the measured parameters was checked using the coefficient of variation (CV) calculated by dividing the standard deviation by the mean value of the parameters (sd and mean function in R Development Core Team 2018). A one-way ANOVA was then performed with the different variables collected on the treatments (harvest, fruit diameter, LAI and Ψ_{stem}) followed by a Tukey test for pairwise comparison. The variability of the sample means in the parameter distribution was determined through the standard error (SE) of the mean.

In order to calculate the daily distance (d) per day, the following steps were undertaken:

- In the initial stage of the analysis, a basic linear regression (SD vs. VPD) was conducted for each tree. The same regression was subsequently analysed separately for stress and unstressed periods (water stress: $\Psi_{stem} \leq -1.5$ MPa; unstressed: $\Psi_{stem} > -1.5$ MPa).
- In a second step, a reference period was delineated (07 July–14 July 2022), upon which a new linear regression (SD vs VPD) was calculated for each tree. Subsequently, the intercept and slope values were recorded. This represents the intercept and slope derived from the reference equation.
- Subsequently, the data from the remaining days of the experiment (15 July–26 July 2022) were further analysed, and a linear regression was conducted for each day and for each tree.
- The difference between the two regression lines (first weeks – reference and remaining days) was calculated for each tree using Eq. 2

$$distance(d) = sqrt\left(Slope_{reference} - \quad Slope_{day}\right)2 + \left(Intercept_{reference} - \quad Intercept_{day}\right)2 \tag{2}$$

Where, "d" represents the difference between the "reference" regression, which was calculated during the initial week when the stem water potential Ψ_{stem} was greater than −1.5 MPa, and the "daily" regression, which was calculated for consecutive days when Ψ_{stem} was less than or equal to −1.5 MPa. The term "sqrt" denotes the square root function used in *R* Studio, which may be applied to specific calculations within the model. The slope of the regression line from the reference period, where Ψ_{stem} is greater than −1.5 MPa, is referred to as the slope of the reference. This provides a baseline for non-stressful conditions. The slope of the regression equation for days when Ψ_{stem} is less than or equal to −1.5 MPa represents the slope from the regression equation for days when stress conditions are indicated. The term "intercept reference" refers to the intercept from the reference regression equation, whereas "intercept day" denotes the intercept from the daily regression under stressed conditions.

Finally, a simple linear regression was employed to predict the Ψ_{stem} data, utilizing the daily distance "d", minimum values of TWD per day and the average VPD per day (Eq. 3).

$$water\ potential = lm(d/day + \min.twd + avg.VPD) \tag{3}$$

In the equation, d/day represents the difference between the regression of the reference period (first week) and the regression of each consecutive day during the experiment. The min. TWD stands for the minimum tree water deficit observed per day, VPD refers to the vapor pressure deficit.

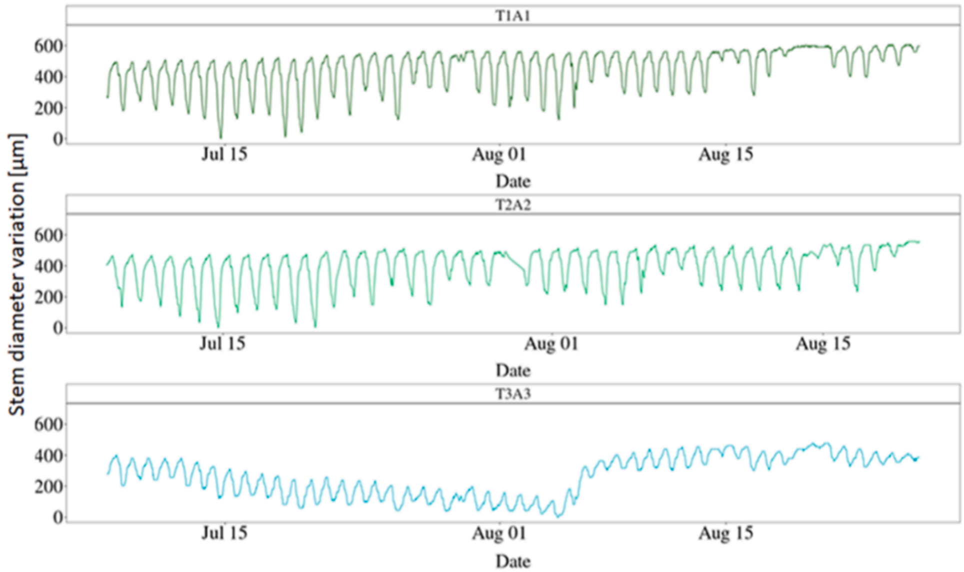

Fig. 3. Daily stem diameter movement, shrinkage at sunrise, and expansion at sunset. The graph shows three trees, one from each treatment (top = T1, middle = T2, and bottom = T3).

3. Results

The summer of 2022 was very hot and dry compared to the previously years. A long period without rain from 05/07/2022–13/08/2022 with high temperatures up to 35°C created Ψ_{stem} below −2.0 MPa. The different irrigation treatments resulted in varying levels of stress among the trees. Below, we present the impact of these treatments on tree performance, water status, and dendrometer reference parameters, as well as a potential model for estimating tree water status using weather data and dendrometer measurements.

3.1. Weather conditions and irrigation

The average, maximum, and minimum temperature are displayed in Fig. 4 for the period of the experiment. During the experiment (01 July–26 August 2022), the maximum temperature was 36.5°C. The values for VPD and ET0 are presented in Fig. 5. The maximum average value for VPD was 2.3 KPa, while the maximum value observed over the course of a minute was 4.8 KPa. The maximum ET0 was 5.6 mm per day. The greatest quantity of precipitation recorded in a single day was 10.41 mm.

The effective irrigation period took place between July 26 and August 25, 2022, resulting in T1 receiving a total of 130 mm, T2 approximately 91 mm, and T3 with nearly 10 mm of water (Fig. 6). On average was irrigated 2.6 mm per day in the T1 treatment

3.2. Water stress effects on production

The applied treatments T1 (full irrigation), T2 (70 % irrigation), and T3 (no irrigation) exhibited a significant effect on yield ($p < 0.05$) (Fig. 7 A). T3, without irrigation, had a significantly lower yield than T1 (100 % irrigation), while T2 (70 % irrigation) fell between the two. The total number of fruits showed no significant differences between treatments, with an average of approximately 126 apples per tree. The last measurement of fruit diameter (22/08) was also not significant different, ranging from 61(T3) to 68 mm (T1).

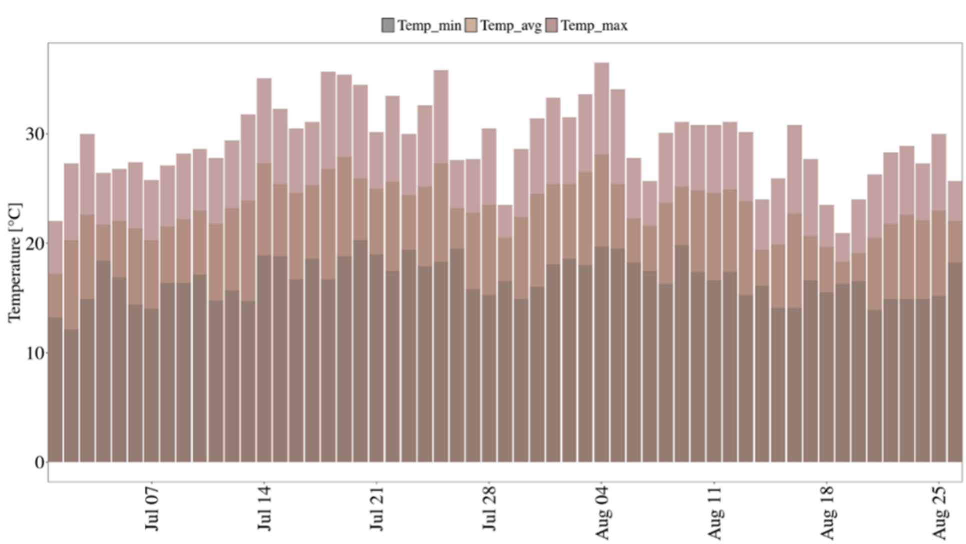

Fig. 4. Temperature (minimum, average, maximum) measured by the weather station (on the plots) at the experimental orchard in Grens Village, Canton Vaud during July and August 2022.

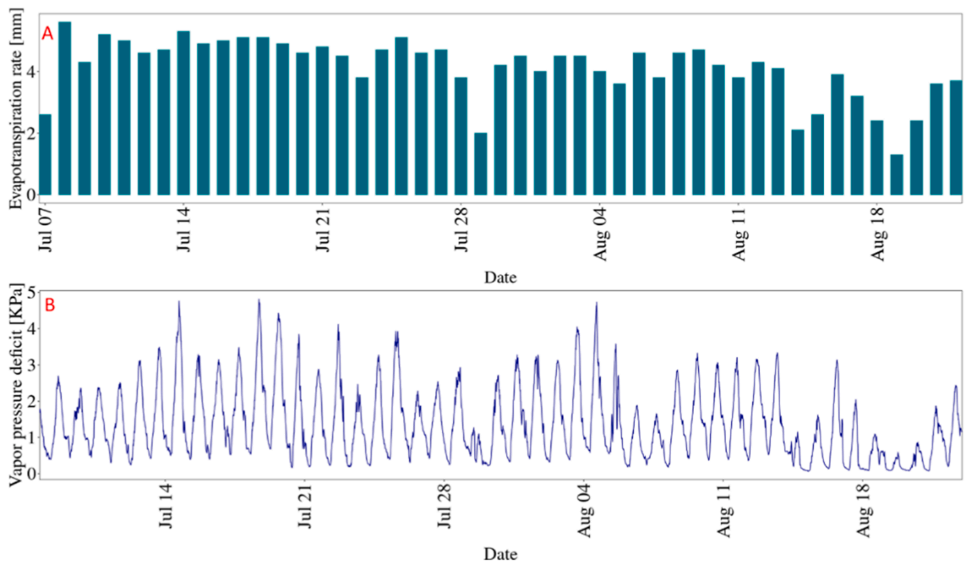

Fig. 5. The evapotranspiration rate (A: green) and vapor pressure deficit (B:blue) orchard in Grens Village, Canton Vaud during July and August 2022.

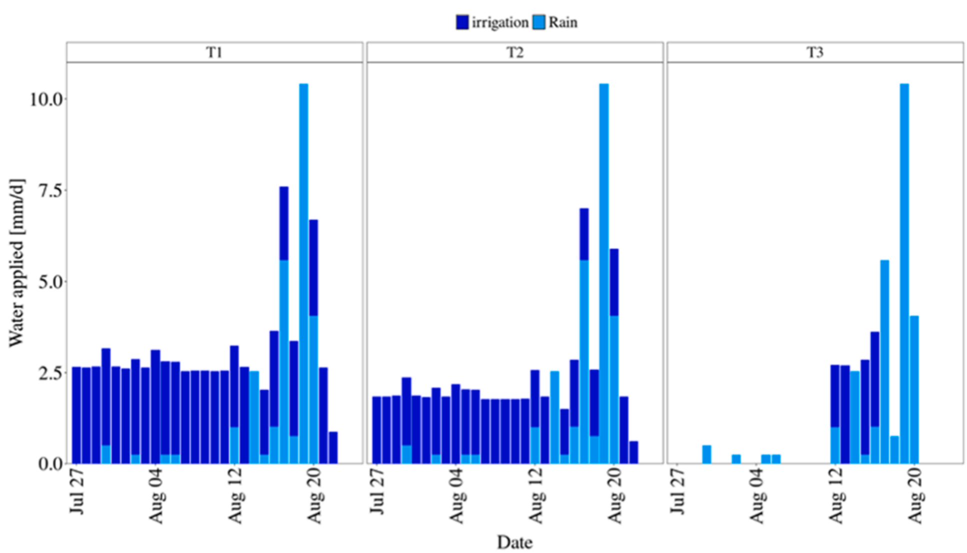

Fig. 6. Amount of water (irrigation + rain) per treatment during the experiment. T1 = soil moisture-based irrigation (100 %); T2 = soil moisture-based irrigation (70 %); T3 = without irrigation (weeks) in blue, and rain in light blue.

Leaf area indexes did not differ significantly; T1 had the smallest LAI (2.5), followed by T2 and T3 (both at 2.6). The average of the individual fruit weights per tree showed the significant ($p < 0.05$) influence of the lack of irrigation on fruit. The 100 % irrigated treatment (T1) had an average of 162 g per fruit, followed by T2 (70 %) with 152 g per fruit and T3 (no irrigation) with 123 g per fruit (Fig. 7 B).

3.3. Tree water status

Measurements of the Ψ_{stem} using the Scholander chamber at noon were carried out from late June to the end of August. Notably, a period of increased water stress, with water potentials below - 2.0 MPa, persisted from July (25/07) to early August (04/08), ended with rainfall (Fig. 8 A). Ψ_{stem} indices were significantly lower in the unirrigated treatment (T3), followed by T2 and, lastly, T1 (Fig. 8 B). Stress levels exhibited a decline of −2.0 MPa for T3, while the control treatment maintained a stable hydric level, experiencing stresses ranging from −1.0 to −1.7 MPa throughout the experiment. T2, with 30 % less irrigation, remained above −1.7 MPa for most of the season.

3.4. Water stress displayed by dendrometer reference parameters

3.4.1. Daily stem diameter variation

The maximum SD was exhibited at sunrise (05:30–07:00). The minimum SD was determined around sunset (20:00–21:45). Subsequently, the 24-hour data were plotted in relation to the VPD values (Fig. 9). At sunrise (dark blue dots) and during the remainder of the day (light blue dots), the maximal SD values had the highest values at the top of the regression line.

A more in-depth analysis was conducted on the experimental data by dividing the data presented above (Fig. 9) into two periods, one period with low water stress ($\Psi_{stem} > -1.5$ MPa) and another with higher water stress ($\Psi_{stem} \leq -1.5$ MPa). Subsequently, these data (SD vs VPD) were plotted again, represented by a blue regression line (unstressed period) and red regression line (stressed period) in Fig. 10 A–C. The distance between the two lines, represented by a "d" in the graph, indicates the difference (derived by the slope + intercept) between the two regression lines. For the fully irrigated treatment, T1 (Fig. 10 A), there was almost no difference (d) between the two regression lines and a small distance

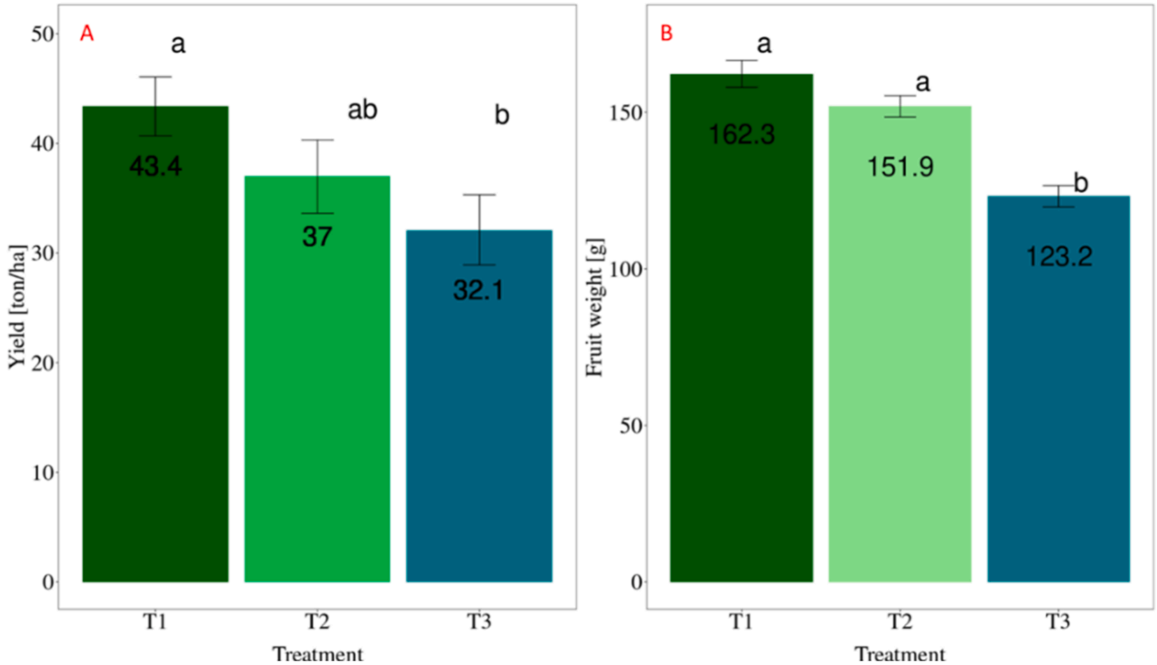

Fig. 7. A, yield in ton per ha; B, fruit weight (g) at harvest; per tree per treatment; Yield parameters collected on 24/08/2022.

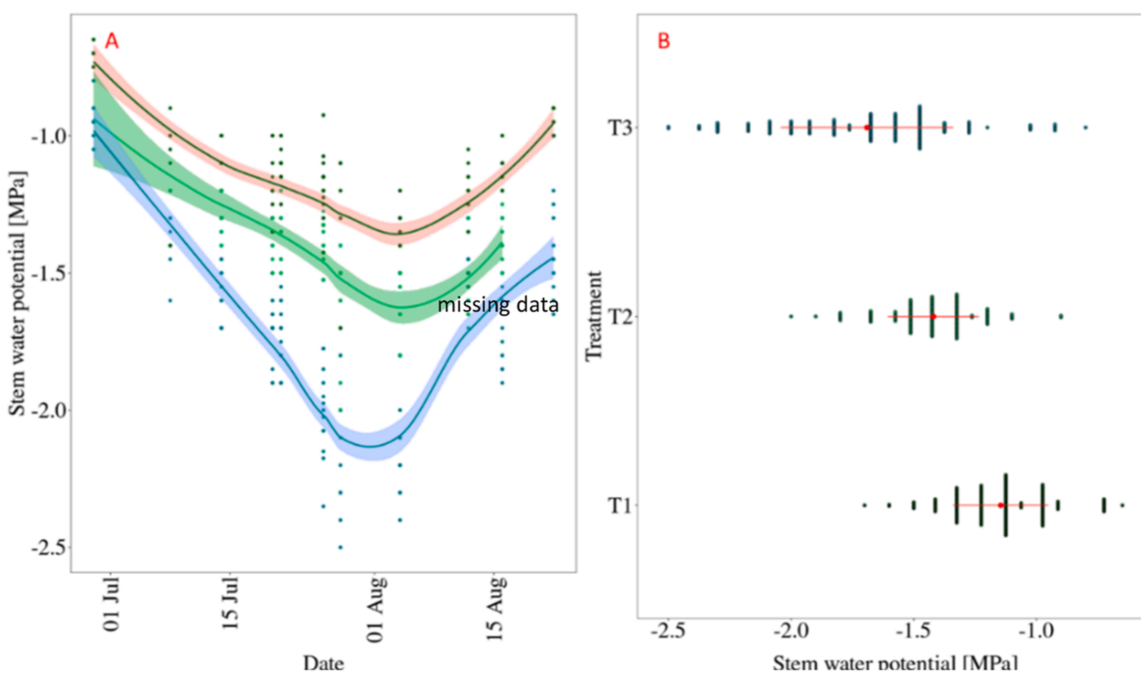

Fig. 8. A, The values of the stem water potential (Ψ_{stem}) (MPa) per date during the whole season of the three treatments T1, T2, and T3. The single lines indicate the mean from measured numbers and the lower and upper of the confidence intervals around the mean. B, Distribution of all Ψ_{stem} (MPa) values per treatment T1, T2, and T3. The length of the lines indicates the number of observations for the corresponding treatment.

(d) was observed by T2 treatment (Fig. 10 B). By contrast, the treatment without irrigation, which led to high water stress (T3), exhibited a considerable distance (d) between the regression lines, with the lines almost parallel and "d" of about 200 µm (Fig. 10 C). Considering all trees, the distance "d" of T3 was significantly higher than that of T1 or T2 (Fig. 10 D).

The result of the distance (d) per treatment is also shown in Fig. 11. In the unstressed period, the values were highest in the 100 % irrigated treatment (T1), followed by the 70 % irrigated treatment (T2), and then the treatment with no irrigation (T3), with a significant difference between them (Fig. 11). In the period with higher water stress (stressed), the pattern is the opposite: the greatest variation in distance ($p < 0.01$) is found in the trees belonging to the treatment without irrigation (T3), followed by the treatment with 70 % (T2) and then 100 % irrigation (T1). No significant difference during the unstressed period (Fig. 11 D). The significant difference during the stressed period was between T2 and non-irrigated treatment (T3) (Fig. 11 -E).

3.4.2. Tree water deficit

The average TWD per treatment is displayed in the Fig. 12 for the

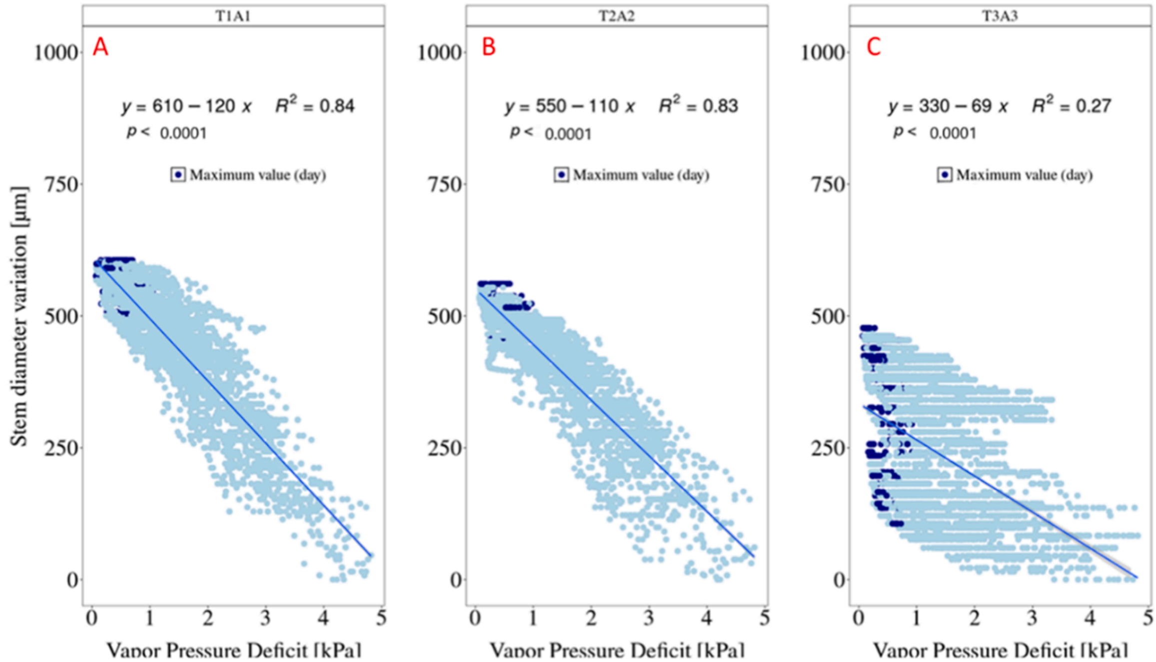

Fig. 9. Simple linear regression of stem diameter and vapor pressure for three trees (one per treatment. A, T1; B, T2; C, T3) in a 24-hour cycle from July – August 2022. (Highlights show maximum values (dark blue) and other values (light blue) during the day.).

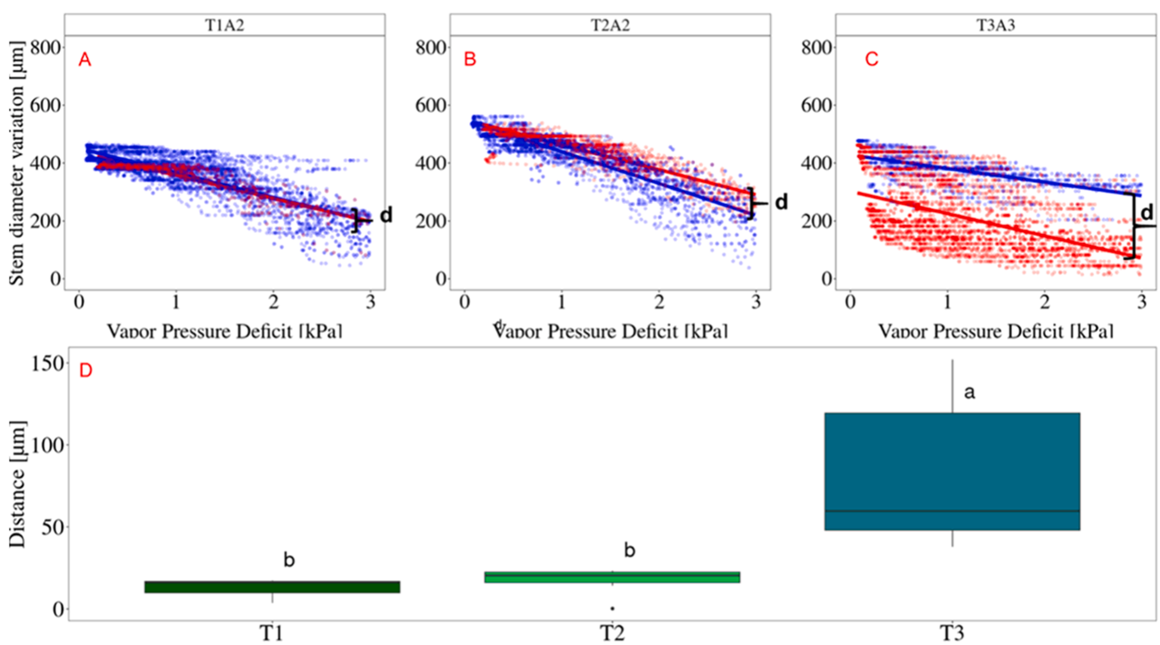

Fig. 10. Daily distances (d) between regression lines (SD vs VPD) for the different periods, unstressed period (blue line and blue dots) and stressed period (red line and red dots) for one tree from T1 (A - T1A1), T2 (B - T2A2), and T3 (C - T3A3). Graph D represents the variation of distances (d) on average per tree by treatment.

whole trial period. Each treatment had water stress peaks at different times. The maximum and minimum values for each treatment were not obtained on the same day. Treatment T3 was the treatment with the most intensified water stress (Fig. 12 A–C). This water deficit was also evaluated following the previous data filter by the unstressed and stressed periods. In the unstressed period, the water deficit was higher in treatment T2, while in the stressed period, T3 showed the highest values (Fig. 12 D and E). The difference between the treatments was not significant in both periods.

3.4.3. *Daily stem diameter variation and stem water potential*

A simple linear regression was calculated from the data previously reported, where the Ψ_{stem} data collected on a weekly basis were estimated by the relationship between the distance "d" (distance between the regression lines presented above Fig. 11 A-C) per day and the minimum TWD value (lm($\Psi_{stem} \sim$ d/day × min.twd), $r^2 = 63$ %, $p < 0.001$). Adding the average VPD values per day strengthened the regression (lm ($\Psi_{stem} \sim$ d/day + min.twd + avg.VPD), $r^2 = 66$ %) Fig. 13. The statistical summary results are presented in Table 1.

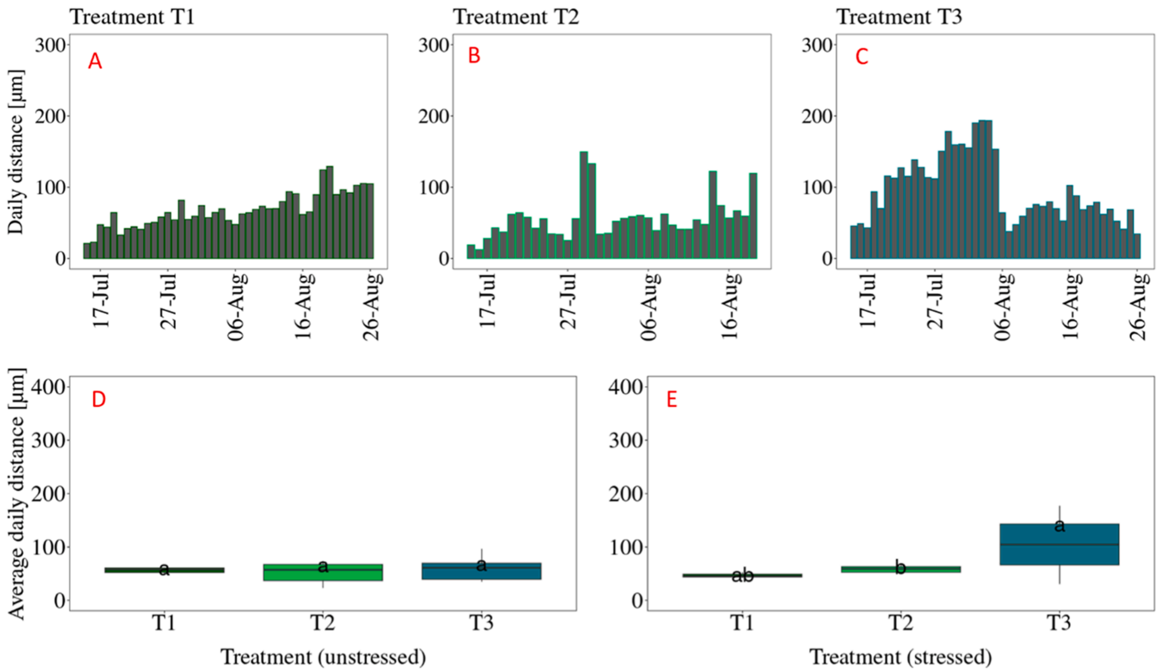

Fig. 11. Distance per day variance per treatment and per period **unstressed**: Ψ_{stem} > -1.5 MPa and **stress**: $\Psi_{stem} \leq$ -1.5 MPa (T1, 100 % irrigation; T2, 70 % irrigation, and T3, without irrigation).

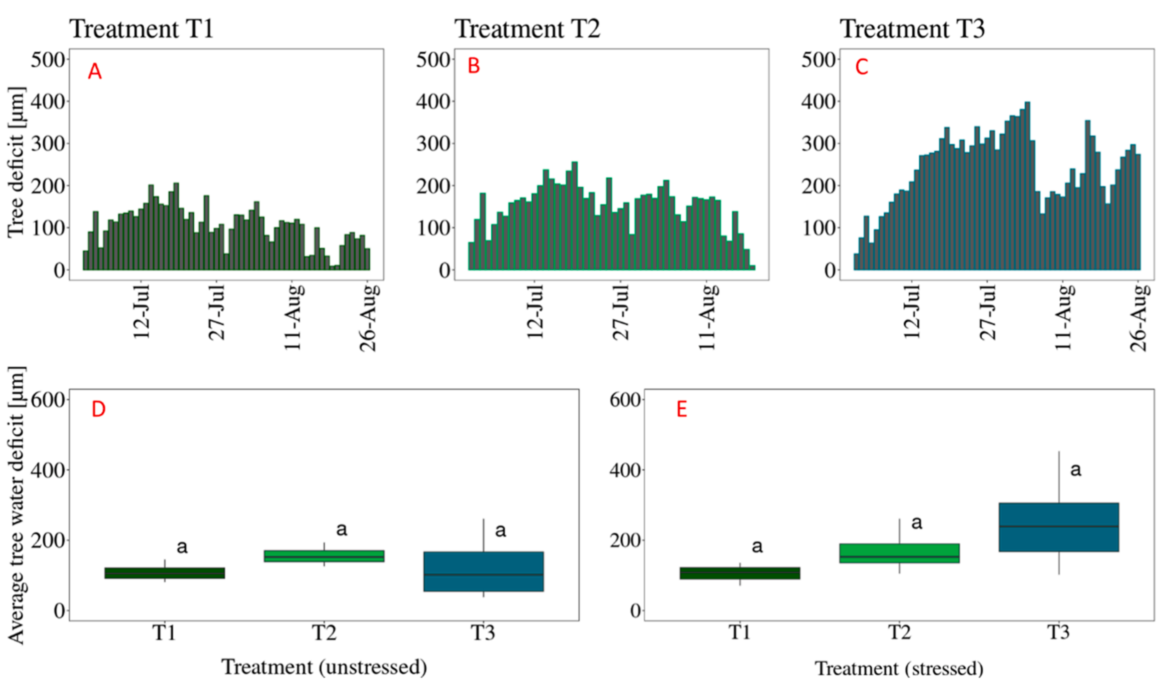

Fig. 12. Tree water deficit (TWD) per day per treatment (A, T1; B, T2; C, T3) and the average TWD per period D: **unstressed**: Ψ_{stem} > -1.5 MPa and E: **stress**: Ψstem ≤ -1.5 MPa.

4. Discussion

4.1. Weather conditions and irrigation levels

The weather conditions during the course of the experiment provide insight into the factors that influence crop water usage, irrigation needs, and overall plant stress. The temperature fluctuations influenced both VPD and ET0, which are very import for the comprehension of crop water requirements (Chang et al., 2024). Fig. 5 provides further context on the crop water demand by presenting VPD and ET0 values. Furthermore, the highest recorded VPD of 4.8 KPa indicates periods of intense atmospheric demand for water, which is likely to intensify plant water stress. Similarly, the peak ET0 value of 5.6 mm/day serves to illustrate a considerable demand for water due to evaporative processes, thereby underscoring the necessity for consistent irrigation in order to maintain optimal plant health and yield under such conditions. The rain was not so intensive during the trial with a peak of 10.41 mm per day. Fig. 6 illustrates the effective irrigation amounts for the three treatments

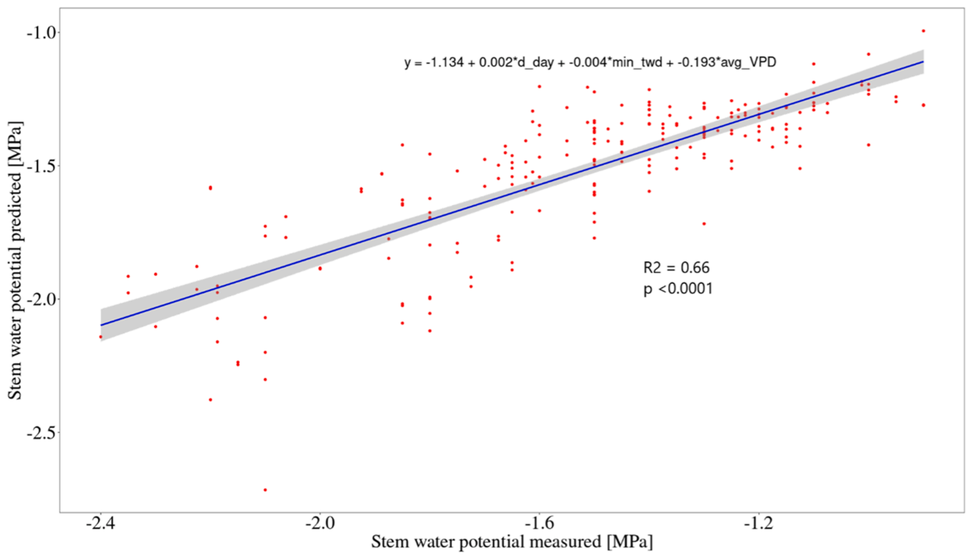

Fig. 13. Comparison of linear regression model predicted (y-axis) and actual measured (x-axis) stem water potential measured every week.

Table 1
Summary output from the simple linear regression model for average Ψ stem using predictors like day distance (d day), minimum TWD, and average VPD with their statistical details.

	Average Ψ_{stem}		
Predictors	*Estimates*	*Confidence Interval*	*p-value*
(Intercept)	−1.134	−1.285 – −0.983	**< 0.001**
d day [1st degree]	0.002	0.001 – 0.002	**0.001**
Min TWD [1st degree]	−0.004	−0.004 – −0.003	**< 0.001**
Avg VPD [degree]	−1.92	−0.293 – −0.092	**< 0.001**

R^2/R^2 adjusted 0.659 / 0.654
Observations = 217

(T1, T2, and T3), demonstrating notable differences. T1 received the greatest volume of irrigation, followed by T2 and T3. This range of water applications allows for comparisons in plant response across different levels of water availability, which could help determine optimal irrigation practices under high VPD and ET0 conditions.

4.2. Response of growth and yield parameters to water stress

Experiments involving trees often have to consider the tree as a single individual in the experiment, mainly due to the variability between trees. However, in this study, the trees within the treatments were not significantly different in terms of vegetative growth, that is, the leaf area index (LAI), ranging from 2.5 to 2.6, aligning with typical values for Gala trees at this stage (between 2.14 and 3.05) (Guo et al., 2015).

The yield decrease was notable in the treatment without irrigation (T3), dropping by about one third to 32 tons/ha, while the fully irrigated T1 achieved a yield of 43.4 tons/ha. This drop was expected, given that the trees received less than 8 % of water compared to the fully irrigated treatment. Treatment T2, with 30 % less water than T1, exhibited a 13 % yield loss, reaching 37 tons/ha. These yields surpassed the annual average in Switzerland (around 30 tons/ha of the Gala variety [Malus domestica]) (Obstverband et al., 2008).

Fruit quantity was not affected by the amount of water irrigated, which confirms findings of previous studies (Plavcová et al., 2023a, b; Tian et al., 2019), suggesting that the thinning process determines fruit quantity. This was confirmed by the fact that very little fruit fall was observed in all treatments throughout the season, and fruit setting was controlled with hormones as well as through manual thinning by the farm. The amount of irrigated water was also observed through the average weight of the fruit. The average individual fruit weights per tree displayed the influence of the lack of irrigation in T3 ($p < 0.05$), with the fruit from this treatment weighing 123 g. Fruit weight did not decrease significantly compared to the fully irrigated treatment when 30 % less water was applied (T2). A fruit must have an average weight of 90 g to meet the sales criteria (Obstverband et al., 2008). This criterion was met in all treatments. The lowest average individual fruit weight per tree was 98.2 g, recorded in T3.

4.3. Stem water potential

During the experiment period until mid-July, all trees remained within a comfort zone with a Ψ_{stem} above −1.5 MPa. For apple trees, values below −1.5 MPa indicate water stress (De Swaef et al., 2009), with values that fall below −2.0 MPa considered significant water stress beyond the tolerance levels for commercial production (Wheeler et al., 2023). Subsequently, water stress was initiated around July 14 and lasted until August 12. This period was marked by no precipitation and relatively high temperatures of up to 30°C. During this phase, treatment T1 effectively kept trees above the stress level (Ψ_{stem}) of −1.5 MPa. The treatment T2, with reduced irrigation, maintained Ψ_{stem} within a range of −1.2 to −1.5 MPa. However, treatment T3, without irrigation, resulted in substantial stress levels with Ψ_{stem} beyond −2.4 MPa. Ψ_{stem} values gradually decreased after the first week of August in all three treatments due to rainfall (approx. total of 40 mm) and milder temperatures (below 30°C). These high values of Ψ_{stem} reached in T3 explain the reduction in production. Kendall et al. (2022) suggested a relationship in which a yield increase of 5.9 kg per tree correlated with a Ψ_{stem} decrease of 0.1 MPa over a period of two production seasons (2019 and 2020). However, in this study, yield decreases by about 1.12 kg per tree for each additional MPa increase in water stress during this single production season (data not shown). It is crucial to note that the plant and soil physical characteristics, as well as the climatic conditions, influence this relationship and cannot be simply compared.

Considering the stress indicated by soil moisture sensors, Ψ_{stem} did not respond accordingly. At the trial's onset (around 08 June 2022), T3's Ψ_{stem} was above −1.5 MPa. However, the soil sensors indicated high levels of stress, with matric potential values exceeding −300 kPa, the upper measuring limit of the Watermark sensors used. This reading signals extremely dry soil conditions. This indicates that the trees were able to extract water that was not measurable by the soil moisture sensors placed at a depth of 50 cm in the middle of the tree rows. The discrepancy between these two water stress indicators aligns with findings by Kendall et al. (2022), emphasizing that even with high values from soil moisture sensors, Ψ_{stem} did not necessarily confirm this stress. This observation echoes the findings of (Steppe et al., 2008), highlighting that plant-based stress is not accurately represented by soil moisture. In contrast, yield decreases correlated well with stem water potential.

4.4. Dendrometer measurements

The dendrometer measurements indicated that the daily SD variation reflected the climatic constraints very well, supported by the linear correlation with the VPD of the air (Fig. 9: T1 & T2). However, when Ψ_{stem} values continued to increase, the correlation between the two parameters tended to decrease (Fig. 9: T3). These results indicate that after a certain water stress, tree shrinkage/expansion reflected by the diameter values of the stem is limited, most likely due to insufficient water uptake at night, leading to incomplete water uptake and swelling overnight (recovery period). Consequently, SD did not return to the value observed at the beginning of the day, resulting in a considerably lower SD maximum than the previous day. This result reflects the restricted movement of the stem when water becomes a limiting factor. The literature describes this pattern as a negative daily net growth (Deslauriers et al., 2003).

The limitation of stem movement was also observed in this study with MDS measurements (data not shown). T3 trees reached a peak MDS of around 600 μm with a Ψ_{stem} value of −1.7 MPa; afterward, the MDS decreased with decreasing Ψ_{stem} values. The same outcome was reported by Huck and Klepper (1977) and Ortuño et al. (2009), who demonstrated decreasing MDS values with increasing water stress. Cohen et al. (2001) and De Swaef et al. (2009) also noted that MDS did not increase when Ψ_{stem} reached −2.0 MPa in their peach tree study. De Swaef et al. (2009) addressed this MDS pattern change by calculating a modified MDS, in which they computed MDS based on the difference between the maximum stem diameter per day in the control treatment (T1) and the minimum stem diameter per day in the treatment with water limitations (T2 & T3). The MDS values obtained with this methodology more accurately describe the water stress of the tree, as confirmed by our study (data not shown). The difficulty of this method lies in maintaining an area without water stress to serve as a basis for reference values (unstressed treatment) (Naor and Cohen, 2003). Further, Ortuño et al. (2010) and Tian et al. (2023) suggested that MDS values can be considered a robust climate stress indicator when soil water content is not excessively depleted, which is fully in line with our observations.

Of all the dendrometer-derived parameters, two reflected water stress applied to trees in treatment T3. One of these parameters was the distance “d” calculated between the linear regression distances (intercepts + slopes) of a tree (SD vs VPD). This was tested separately by period in two periods ($\Psi_{stem} > -1.5/\Psi_{stem} \leq -1.5$ MPa Fig. 10) as well as by day. The greater the water stress, the greater the distance between these two regression lines (Fig. 10 D). The regression performed on the first week of data collection (reference regression) and the other days of the experiment per tree also confirmed this trend (Fig. 11 A–C). The greater the distance between the reference regression line and regression lines for the other consecutive days, the greater the water stress. Plotting the data by treatment showed that the greatest distance “d” was found in the treatment with the greatest water stress. We found no difference in distance “d” between treatments in unstressed situations. However, in stressed situations ($\Psi_{stem} \leq -1.5$ MPa Fig. 11 A–E), a significant difference was detected between the treatments. Goldhamer and Fereres (2001), also used the slope variations in regression lines derived from the daily maximum and minimum stem diameter values to differentiate between stressed and unstressed young peach trees (n = 4). Their findings indicated that the stressed trees exhibited lower slopes over time compared to those in the unstressed treatment.

The second parameter that also responded to the water stress applied in the T3 treatment was TWD (Fig. 12 C). This parameter is widely used in forestry research (Zweifel et al., 2016). The treatment without irrigation showed the highest values ((Fig. 12, T3) being quite consistent with the water stress that was applied. However, it did not show any significant difference when evaluated against the unstressed and stressed periods (Fig. 12 D, E). In the daily irrigated treatments (T1 & T2), the values follow a similar pattern with the same period of increase and decrease. In treatment T3, values increased daily until the end of July, followed by a drop in TWD around July 27. This decrease in TWD values was observed in all treatments and was directly related to the start of the rainy period.

4.5. Tree water status model

We found that three key parameters, irrespective of water stress levels, reflected the trees’ water status: the distance “d” between regression lines obtained from the SD–VPD regression in the first week (reference regression) and those of the other consecutive days (Fig. 11), the TWD (Fig. 12), and the VPD. We used this observation to develop a model refer to stem water potential (Ψ_{stem}), which could be used for irrigation scheduling. A reasonable correlation was found with linear regression models, in which the interaction of the minimum daily value of the TWD and the distance “d” reflected 63 % of the water potential data. This interaction was further confirmed by incorporating average VPD values (r^2 = 66 %). The correlation was significantly improved using a second/first polynomial model (r^2 = 70 %), but this was due to overfitting the model. In severe water stress reports, polynomial and exponential regressions often outperform linear ones (Cohen et al., 2001; Paudel et al., 2015). By comparing the original Ψ_{stem} data with the Ψ_{stem} data predicted by the model, it is apparent that the model works best when water stress is visible ($\Psi_{stem} \leq -1.5$ MPa). This irrigation-scheduling model could be conservative and suitable for automation with dendrometer sensors and a weather station. However, it’s important to note that this model was developed using a limited dataset, covering only two months of a single growing season. The potential effects of crop load on the model’s accuracy were not tested. Dietrich et al. (2018) presented a model expressing Ψ_{stem} through logarithmic regression (r^2 = 69 %) of the relative values of TWD data (n = 6) from European tree species in dry to wet conditions in the forest. Applying the same model in this study yielded a weaker relationship (approximately r^2 = 59 %). These relationships need to be confirmed with other fruit varieties, species, and environments. Nevertheless, the good correlation with the well-known TWD shows that adaptation to different circumstances should be possible.

4.6. Dendrometer as a stress indicator sensor

The experiment highlights considerable challenges in employing dendrometer sensors due to notable tree-to-tree variability and the maintenance of the sensor in the tree (mounting, cables, and connections). Compared to the Ψ_{stem} data, the data obtained by the dendrometer were more variable (around 60 % variation in measurements), which is in line with the high coefficient of variation (CV) found in the study by Naor and Cohen (2003) and Fernández and Cuevas (2010), who noted that daily variation measurements are derived from the living bark parts, contributing to each tree’s unique characteristics influenced by differences in living tissue width and water flow resistance. It is assumed that greater water stress corresponds to higher CV (Naor and Cohen, 2003), confirmed by elevated CV values in parameters experiencing greater stress. In the present study, treatment T3 exhibited the largest variation among all the parameters analyzed (SD > d_day > TWD > MDS > yield > Ψ_{stem}). Based on a study of apple trees, Naor (2006) concluded that achieving equivalent variation requires 17 SD tree measurements compared to 5 Ψ_{stem} values. Although the variability from tree to tree adds complexity to the data analysis, this could be corrected by improving the material used to attach the sensor to the tree and the selection of representative trees within an orchard, which will have to be more deeply evaluated.

Furthermore, our results suggest that irrigation could likely be controlled more precisely using dendrometer sensors rather than soil moisture sensors, as soil moisture measurements do not accurately represent the effective root zone. Above all, the measurement principle in question is economically available and reliable, demonstrating a robust correlation with Ψ_{stem} when combined with average VPD data.

5. Conclusion

The daily variation in the SD measured by means of dendrometers was closely correlated with the VPD under noon – stressed conditions. The water stress reached in the trees negatively impacted the final yield, particularly in the treatment without irrigation (T3). This highlights the importance of water availability. The Ψ_{stem} proved reliable in assessing water stress. Apple trees in T3 experienced substantial stress levels, thereby showing a shift of the regression line (SD vs VPD) and change in MDS patterns. Further, a simple linear regression model that incorporated the interaction of minimum TWD values, average VPD values, and the shift "d" values per day derived by the regression lines (reference day and actual day) reflected the Ψ_{stem} values. Our findings illustrate that dendrometers, combined with climate data, present the possibility of replacing labor-intensive Scholander measurements and have the potential to be used for the automation of irrigation. However, the implementation of dendrometer sensors was found to present certain difficulties due to the inherent variability between individual trees. This highlights the necessity for a greater number of sensors to be employed. Further, dendrometers are very sensitive to external perturbations, as they measure in a range of about 5–10 micrometers. The simplicity and low cost of dendrometers make them a suitable tool for implementation in automated irrigation systems.

CRediT authorship contribution statement

Nasser Hassan- Roland: Writing – review & editing, Visualization, Validation, Investigation, Formal analysis, Conceptualization. **Monney Philippe:** Writing – review & editing, Validation, Investigation. **Walter Achim:** Writing – review & editing, Writing – original draft, Visualization, Supervision. **Cockburn Marianne:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Investigation, Data curation, Conceptualization. **Waldburger Thainna:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Anken Thomas:** Writing – review & editing, Writing – original draft, Validation, Supervision, Investigation, Formal analysis, Conceptualization. **Hatt Matthias:** Investigation, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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